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JAN 77 C HAHIN, J GAMBILL, J K SCOTT

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CONSTRUCTION ENGINEERING RESEARCH LABORATORY (ARMY)
CHAMPAIGN, ILLINOIS

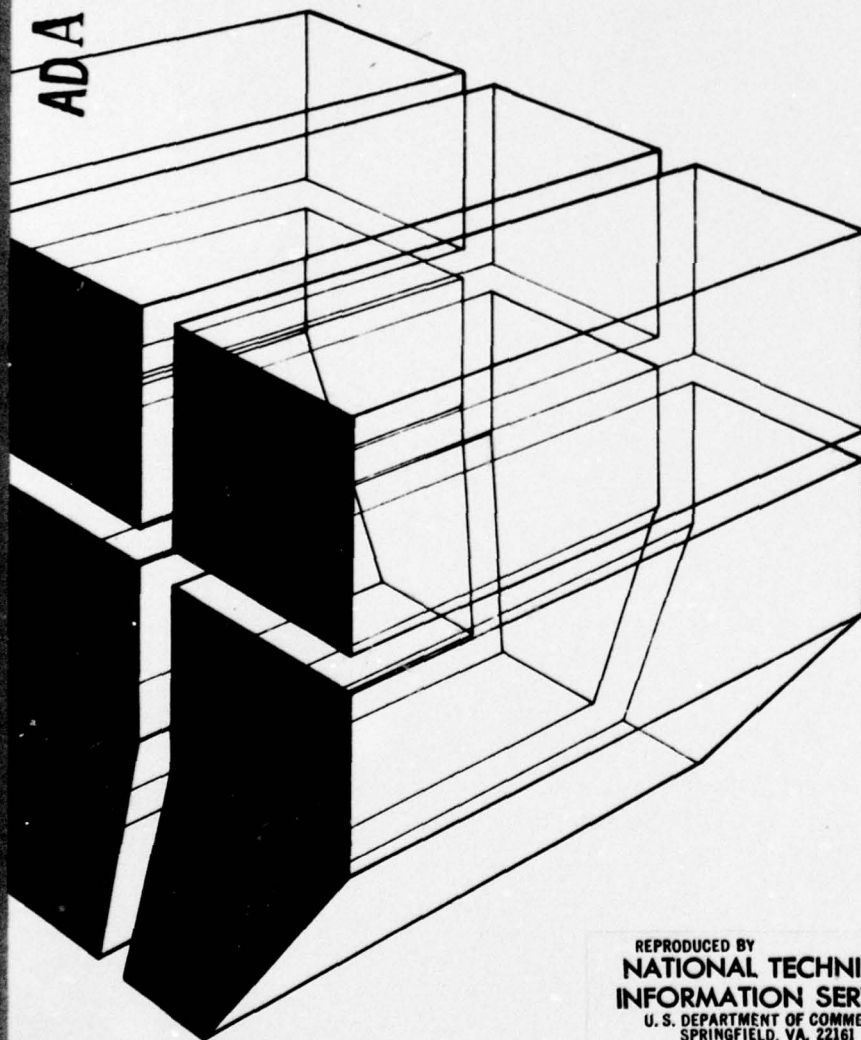
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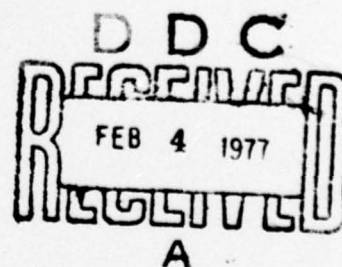
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AN INVESTIGATION OF THE SUSCEPTIBILITY OF POST-
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Post-tensioning cables having ultimate tensile strength (UTS) of 270 ksi (1862 MPa) and satisfying ASTM Standard A-416 were stressed to 80 to 95 percent UTS and exposed to 3.5 percent sodium chloride and saturated calcium hydroxide solutions, where pH values ranged from 8 to 12.5. After 900 hours, since no failures were experienced, cables were forced to rupture. No appreciable reduction in strength resulted, except in cables that were artificially notched (strength losses were not due to corrosion). However, rapid failures at 95 percent UTS occurred when cables were immersed in a dilute hydrochloric		

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acid solution where pH values ranged from 1 to 2. Time-to-failure at pH 2 averaged about 100 hours, whereas at pH 1 time-to-failure was about 1 hour.

FOREWORD

This research was conducted for the Directorate of Military Construction, Office of the Chief of Engineers, under Project 4A762719AT41, "Design, Construction, and Operations and Maintenance Technology for Military Facilities"; Task 07, "Materials Research and Development for Military Construction"; Work Unit 002, "Corrosion Effects on Construction Materials." The applicable QCR number is 1.03.007. The work was performed by the Metallurgy (MSM) and Structural Mechanics (MSS) Branches of the Materials and Science Division (MS), U.S. Army Construction Engineering Research Laboratory (CERL), Champaign, IL. The OCE Technical Monitor for the study was Mr. C. Damico.

CERL personnel directly connected with the study were J. Gambill, J. Scott, J. Gill, W. Mattheessen, C. Hahin, A. Kumar, and E. Cox. The study was suggested by R. Quattrone.

Dr. A. Kumar is Chief of MSM, Dr. W. E. Fisher is Chief of MSS, and Dr. G. R. Williamson is Chief of MS.

COL J. E. Hays is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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AN INVESTIGATION OF THE SUSCEPTIBILITY OF POST-TENSIONING CABLES TO STRESS-CORROSION CRACKING

1 INTRODUCTION

Objective

This investigation was performed as part of a long-term study to evaluate the effects of corrosive environments on structural materials having contact with Portland cement concrete. The study is primarily concerned with determining which factors affect the life spans of steel alloys.

This report evaluates the effects of typical corrosive environments on the longevity of post-tensioning cables and investigates the possibility of their rapid, premature failure.

Approach

The authors reviewed post-tensioning cable failures reported in the literature and analyzed corrosion tests of cables conducted by other researchers. An experimental study of load vs. time-to-failure was conducted in which unnotched and V-notched cables were exposed to both basic and acidic media. Notched specimens were not precracked and were not fatigued in tension.

Background

Post-tensioned structures have generally provided trouble-free service, experiencing very few failures and little tendon corrosion. However, this information is based on knowledge of structures whose service lives are generally 25 years or less. As the volume of post-tensioned construction steadily increases, there is growing concern about the extent of corrosion damage during long-term service. Catastrophic failure resulting from stress-corrosion cracking is of particular concern.

The high-strength steel used in post-tensioned structures is surrounded by concrete and grout, which provide a protective environment for the steel. Failure from stress corrosion can be expected to occur only when this protection breaks down. Failures occurring in post-tensioned structures have resulted from the presence of a corrosive environment around the steel. Corrosive materials can come in contact with the steel as a result of improper construction procedures, inadvertent inclusions of chemicals harmful to the concrete, or an insufficient or cracked concrete grout cover.

Chlorides, fluorides, sulfites, and nitrates are known corrosives whose concentrations in the grout are specifically limited by ASTM C-150.¹ Early failures of post-tensioned structures have been traced to each of these chemicals.² Failure analysis has also indicated that the heat-treated and oil-quenched-and-tempered steel wire used extensively in Europe is more susceptible to stress-corrosion cracking than the cold-drawn wire commonly used in the United States.³

The Highway Research Board⁴ conducted an extensive study on steel in prestressed concrete bridges. Results indicated that if the original concrete cover is adequate and does not deteriorate, the steel tendons will remain free from corrosion. During this test, the longest run on unprotected wire in a corrosive environment was for 49 days in 3.5 percent sodium chloride solution, with stresses to 225 ksi (1550 MPa).

Mode of Technology Transfer

Specifications and standards potentially affected by this report are:

- (1) MS-17339D, *Cable, Safety (Wire Rope)*, 27 Mar 67.
- (2) MIL-R-2878B, *Rope, Wire, Steel (Carbon) High Strength (for Target-Towing Hawsers)*, 10 Sep 62.
- (3) CE 1401.04, *Prestressed Concrete*, Aug 1969.

2 EXPERIMENTAL MATERIALS, PROCEDURES, AND APPARATUS

Material Tested

The material used in this study was seven-wire stranded Grade 270 steel cable as specified in ASTM A-416.⁵ These wires are made of carbon steel of such quality that when drawn into wire, fabricated into strand, and then properly heat-treated, the strand meets the strength requirements shown in Table 1.

¹ASTM C-150, Part 9 (American Society for Testing and Materials, 1973), p. 137.

²J. Feld, *Construction Failure* (Wiley, 1968).

³B. Genvick, *Construction of Prestressed Concrete Structures* (Wiley, 1971).

⁴"Protection of Steel in Prestressed Concrete Bridges," *National Cooperative Highway Research Program Report 90* (Highway Research Board, 1970).

⁵ASTM A-416, Part 4 (1976), p. 38.

Test Fixtures

The test program placed highly stressed cable samples in a liquid corrosive environment. The test fixture shown in Figure 1 was constructed on a structural load floor testing area. Figure 2 shows a typical cross-sectional view of the fixture and the major components of one cable test station.

Design

As shown in Figures 1 and 2, the fixture was constructed of two pairs of 15 in. x 13 ft (38.1 cm x 3.9 m) steel channels attached to three 10 x 10 in. (25.4 x 25.4 cm) steel columns. The resulting fixture provided two test bays with space for six cable test positions.

In a typical cable test station, loads were applied to the test cable through a hydraulic ram attached to the upper pair of steel channels and through a steel reaction plate. The cable was passed through the hollow center of the hydraulic ram and clamped in place with a standard cable strand chuck. The lower end of the test cable passed through a cylindrical acrylic plastic tank and a steel reaction plate attached to the lower pair of steel channels. The bottom end of the cable was clamped in place with a strand chuck. The bottom of the tank was sealed to prevent leakage of the corro-

sive fluid. This arrangement permitted axial loads to be applied to the test cable while maintaining the corrosive liquid environment around a portion of the stressed cable. The acrylic plastic shields placed across the front of the test fixture permitted close observation of the tests while providing protection against splashing fluid or flying shrapnel if a catastrophic cable failure occurred.

The six hydraulic rams were actuated by a manual pump through a series of control valves and pressure

Table 1

Strength Requirements for Steel Cable as Specified by ASTM A-416

Nominal Diameter of Strand, in. (mm)	Breaking Strength of Strand, lbf (kN)
0.375 (9.53)	23,000 (102.3)
0.500 (12.70)	41,300 (183.7)

Yield Strength Requirements

Initial Load, lbf (kN)	Minimum Load at 1 Percent Extension lbf (kN)
2,300 (10.2)	19,500 (87.0)
4,130 (18.4)	35,100 (156.1)

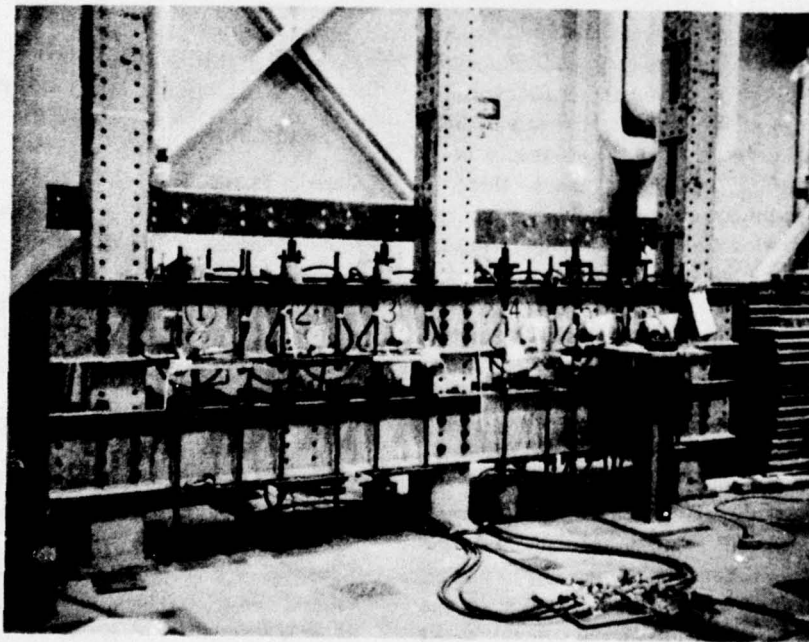


Figure 1. Overall test fixture configuration.

gages, as shown in Figure 3. This arrangement permitted any combination of one or more of the six hydraulic rams to be operated by opening the appropriate control valves.

Cable Failure Sensing

The tests were designed to run 24 hours per day for long periods of time; therefore, a means of continuously monitoring the test cables to record the exact time of failure was devised. The technique consisted of mounting electrical resistance strain gages on the lower steel reaction plates and measuring the flexural strain in the plates during the tests. Each strain gage output was signal-conditioned and recorded on a multi-channel printing recorder, as shown in Figure 4. When a complete or partial cable failure occurred, the change in load and the time of occurrence were recorded while continuous monitoring of the remaining cables was maintained.

Test Procedures

The test procedure used in the experimental program was as follows:

a. A roll of the sample cable was cut into several 48-in. (1.2 m) long test samples.

b. Each cable sample was cleaned prior to testing by soaking in an acetone solvent bath.

c. The lower 6 in. (15.24 cm) of each test cable was dipped in rubberized cement to seal the internal strands of the cable against fluid leakage.

d. The test cables were placed in the loading fixture and clamped in place; rubber cement was placed around the outside strands of the cable at the point where the cable passed through the bottom of the acrylic plastic tank.

e. Each acrylic plastic tank was filled with the test solution, the failure-event recorder turned on, and the load applied through the hydraulic rams.

f. The hydraulic pressure on each ram was recorded periodically and adjusted appropriately to maintain the correct load on each test cable. In addition, the fluid level was checked periodically and fluid added, if necessary.

Test Conditions

The test program was conducted in three phases as described below. Because of time constraints, 900 hours was chosen as the maximum exposure duration for a test cable with no failures.

Phase 1

No artificial notches or precracks were introduced into the test cables. Tests were conducted at various percentages of the ultimate load, using a 3.5 percent sodium chloride and distilled water solution (pH 8). Control specimens were tested at the same load levels, using a saturated calcium hydroxide solution (pH 12.5).

Phase 2

Small V-shaped notches were cut in the six outside strands of each cable (the remaining central strand was not notched) and the tests conducted at the same load levels as in Phase 1. The same test and control solutions were used.

Phase 3

All test cables were notched as in Phase 2, and the same load levels were used. Hydrochloric acid solutions with various pH values were used as test solutions; no control solutions were used.

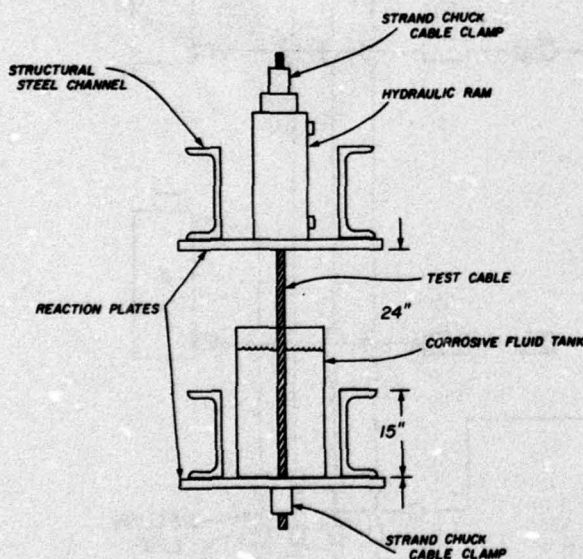


Figure 2. Cross-sectional schematic of a typical cable test station.

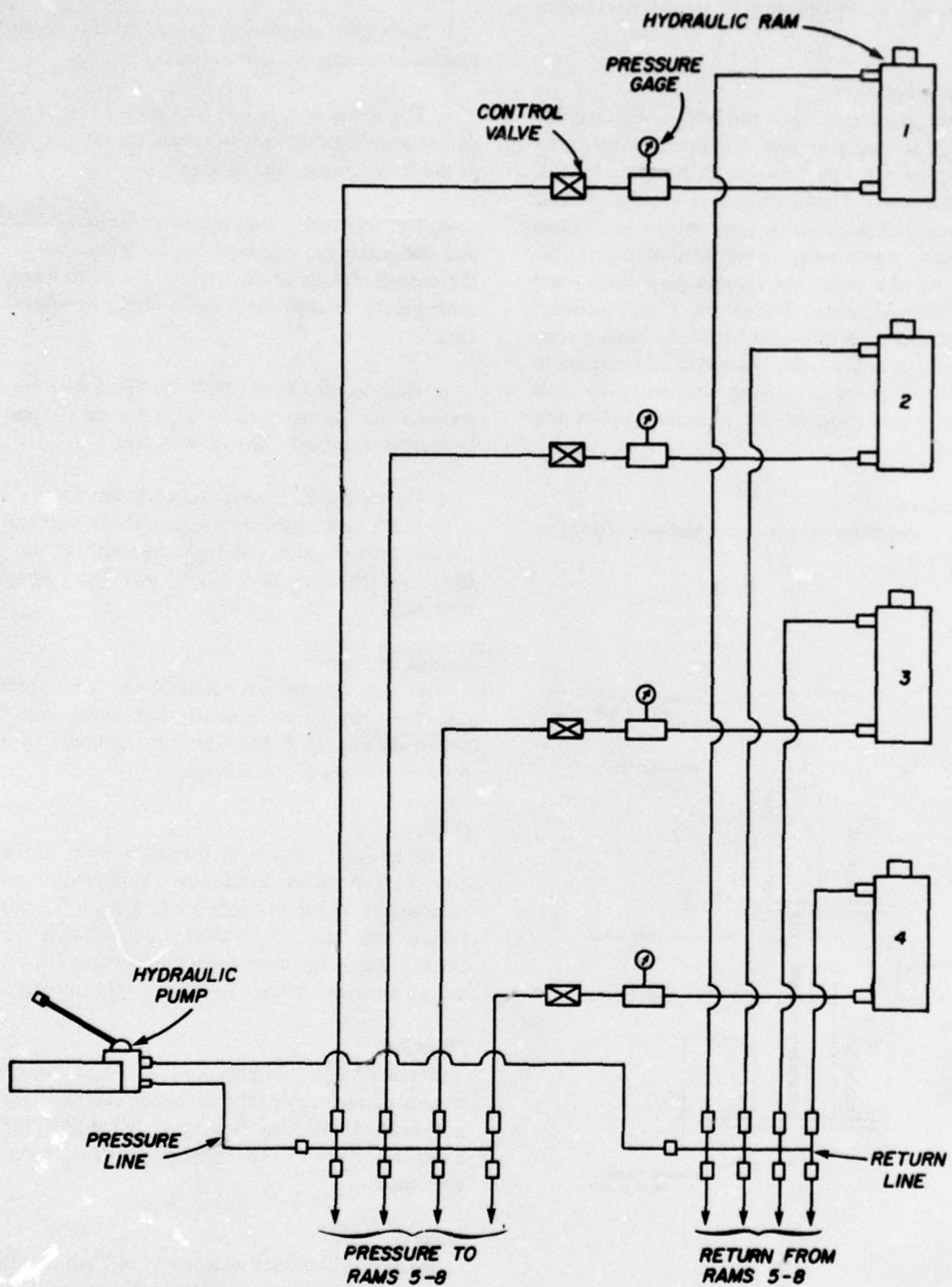


Figure 3. Loading system schematic.

3 RESULTS AND DISCUSSION

Table 2 provides a complete summary of test results. In attempting to establish whether the cables had any sensitivity to stress corrosion, stresses somewhat above service working loads were investigated. As shown in Table 2, no failures occurred before the arbitrary 900 hours termination at approximately 81 percent of ultimate tensile strength (UTS), which is 90 percent of the yield strength (YS). This condition could develop if cables were slightly over-torqued.

Since neither the controls nor the cables exposed to saline solution failed at 81 percent UTS, stresses were increased to 90 percent UTS. Since the cable material is brittle, fractures often resulted in the grips, rather than in the saline solution.

Because of this notch sensitivity in the grips, and since stress-crack initiation accounts for much of the total failure time in many alloys, cable strands were notched prior to immersion with a sharp jeweler's file. Corrosion activity usually initiates in notched areas, so notched cables were exposed to the same corrosive media used in the previous tests. At high stress levels (90 and 95 percent UTS), even with notches, tests had to be terminated after approximately 900 hours with no failures. To determine if load-bearing capacities were diminished, these cables were pulled to fracture. Failures averaged around 22 kips (98 kN), with reductions in strength caused by strand notching.

Finally, the pH of the corrosive medium was changed by using a dilute hydrogen chloride solution at pH 2, which causes the corrosion rate of iron to jump⁶ from the pH 3 to pH 10 plateau. When this corrosive medium is used, hydrogen embrittlement of a crack area can occur, since the tested alloy has little plasticity. At pH 2 and 95 percent UTS, cables failed after an average of 107 hours, breaking one or more strands during fracture. (Failure in this study was defined conservatively as the rupture of a single strand.) With a tenfold increase in acidity at pH 1, the cables failed in 1.25 hours (mean failure time).

Because of time constraints and load frame limitations, full development of postulated threshold stresses could not be obtained. At lower stress levels, these cables may fail rapidly in acidic media (less than pH 3), but not necessarily in chloride solutions with a pH greater than 3.

There appears to be a connection between stress-corrosion crack (scc) propagation rate, pH, and overall corrosion rate. This relationship may be beneficial in predicting the life of cables exposed to low corrosive-rate media, such as cable grouting or cement, which is heavily alkaline (pH>12).

⁶W. Whitman, R. Russell, and V. Altieri, *Industrial and Engineering Chemistry*, Vol 16 (1924), p. 665.

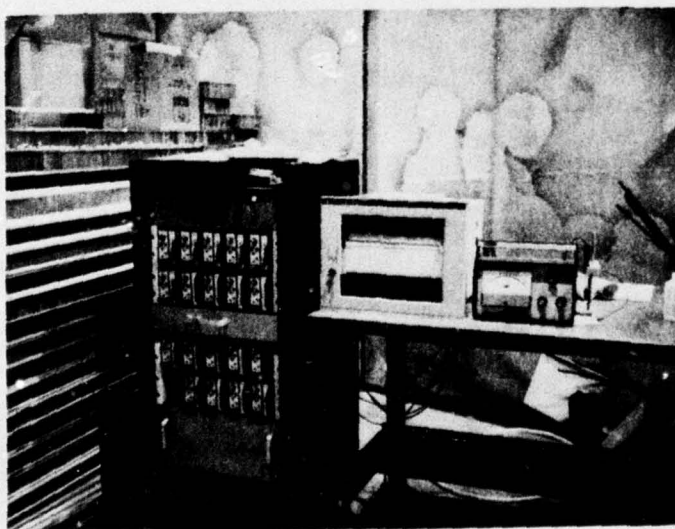


Figure 4. Printing recorder which senses failure and accompanying signal conditioners.

Table 2

Results of Stress Corrosion Failure Tests

Stress Range, % of UTS	Cable Condition and Surrounding Environment	Time to Failure, Hrs	Remarks
81	unnotched; saturated $\text{Ca}(\text{OH})_2$	---	Test stopped at 911 hrs; no failure
81	unnotched; 3.5 percent NaCl solution	---	Test stopped at 911 hrs; no failure
90	unnotched; saturated $\text{Ca}(\text{OH})_2$	---	Test stopped at 911 hrs; no failure
90	unnotched; 3.5 percent NaCl solution	---	Test stopped at 911 hrs; no failure
95	unnotched; saturated $\text{Ca}(\text{OH})_2$	---	Test halted at 864 hrs as cable rup- tured in chuck during adjustment
95	unnotched; 3.5 percent NaCl solution	---	Test halted at 868 hrs by forced failures of cables at 21.93 and 21.87 kips
90	6 strands notched; saturated $\text{Ca}(\text{OH})_2$	---	Test halted at 1176 hrs by forced failure
90	6 strands notched; 3.5 percent NaCl solution	---	Test halted at 1176 hrs by forced failures of cables at 22.25 and 23.16 kips
90	5 strands notched; saturated $\text{Ca}(\text{OH})_2$	---	Test halted at 912 hrs by forced failure at 22.96 kips
90	5 strands notched; 3.5 percent NaCl solution	---	Test halted at 912 hrs by forced failure at 22.45 and 22.96 kips
95	6 strands notched; dilute HCl solution pH 2	72	One strand broke at notch
		142	Failure of single strand; other cables terminated due to leaks or strain gage malfunction
95	6 strands notched; dilute HCl solution pH 1	0.5	Failure of two strands
		2	Single strand failure; others failed in grips or sustained tank leakage

1 kip = 4.45 kN

Using a simplistic analysis, as described by Brown,⁷ for predicting the critical flaw depth for scc, yields

$$a = 0.2 \left(\frac{K_{Isc}}{\sigma_y} \right)^2 \quad [\text{Eq 1}]$$

where a = critical flaw depth
 K_{Isc} = stress intensity for scc
 σ_y = yield stress.

If 15 ksi $\sqrt{\text{in.}}$ (164 MPa $\sqrt{\text{cm}}$) is substituted for K_{Isc} , and 225,000 psi (1550 MPa) for σ_y , only approximately 0.001 in. (0.0254 mm) is required for crack depth to approach conditions sufficient for stress-corrosion crack propagation. The value of 15 ksi $\sqrt{\text{in.}}$ is a conservative estimate based on values for similar high-strength steels. If the Brown equation is assumed to be accurate, there is probably little time required for crack initiation, even at lower stress levels.

During these short-term tests, rapid failure (<100 hours) was not seen for pH 8 nor pH 12.5, but was observed for low pH values. Unfortunately, stress levels were very high, and insufficient data were available to predict performance at lower working stress levels. This is especially important, since cables are often used in applications where ample safety factors are required by law.

Also noted was that the tensile strength was only slightly reduced at the higher pH solutions; this was probably due to normal variations in strength. An

⁷B. Brown, "A Preface to the Problem of Stress Corrosion Cracking," *Stress Corrosion Cracking—A State of the Art*, ASTM STP 518 (American Society for Testing and Materials, 1972), p. 11.

average corrosion rate for these low-alloy steels is about 5 mil/yr (0.0127 cm/yr) overall for various saline media.⁸ One thousand hours is just short of enough time to initiate a notch (based on Brown equation), but whether the crack will propagate is uncertain. It may be necessary to accelerate the corrosion rate to determine if crack initiation occupies the majority of total failure time, or if propagation is the more time-consuming portion.

4 CONCLUSIONS

1. Post-tensioning cables of 250 ksi UTS (1772 MPa) sustained loads which generated stresses of 90 to 95 percent UTS in excess of 900 hours in both saturated calcium hydroxide and 3.5 percent sodium chloride aqueous solutions (Table 2). Since no failures occurred at high stress levels in notched specimens in saturated calcium hydroxide and 3.5 percent sodium chloride in water, cables in these higher pH environments are not stress-corrosion sensitive in a relative sense.

2. Cables at these same stress levels in acidic solutions (hydrochloric acid at pH 1-2) failed rapidly. At pH 2, the cable life span is about 100 hours, with life decreasing to approximately 1 hour at pH 1 (Table 2).

3. Life of ASTM A-416 Grade 270 steel cable appears to depend primarily on the pH of surrounding corrosive media (Table 2).

⁸F. Fink and W. Boyd, *The Corrosion of Metals in Marine Environments* (Baker & Co., 1970), p. 21.